

Comparison of Moderator Performance at LWTS and HPTS

LWTS-6000-RE-A-00

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This document compares the neutronic performance characteristics predicted for the moderators suggested for the Long-Wavelength Target Station (LWTS) and those in the base design of the High-Power Target Station (HPTS) at the Spallation Neutron Source (SNS). All comparisons are done on the basis of “per proton pulse,” in which each proton pulse is 34 kJ of 1 GeV protons on either LWTS or HPTS.

1 Model Descriptions

1.1 Long-Wavelength Target Station

The LWTS configuration used for these comparisons is denoted LW1K32, and is more completely described elsewhere. Configuration LW1K32 includes three moderators, of which two are “slab” moderators and one is a “front wing” moderator. Each of these moderators is viewed from one side only. All moderators have nominal viewed faces of 120 mm (horizontal) by 200 mm (vertical). The reflector (out to a radius of ≈ 500 mm) is beryllium and is cooled with heavy water. This reflector is surrounded by heavy water-cooled iron. Table 1 summarizes relevant characteristics of the target station configuration used for this set of calculations. Although nominal operation is

Proton Energy	1 GeV
Pulse Rate	10 Hz
Average Power	340 kW
Energy per pulse	34 kJ
Proton Beam Shape	rectangular
Proton Beam Size	50x150 mm ²
Proton Pulse	$\delta(t)$
Target	W
Inner Reflector	Be
I.R. Coolant	D ₂ O
Outer Reflector	Be
O.R. Coolant	D ₂ O

Table 1: LWTS parameters used in calculations. All normalizations are performed per 34 kJ-pulse.

considered to be at 10 Hz (and thus 340 kW), the actual repetition rate has yet to be determined; 34 kJ per pulse is the value to be considered constant. Figure 1 shows the general layout of target and moderators for this LWTS configuration.

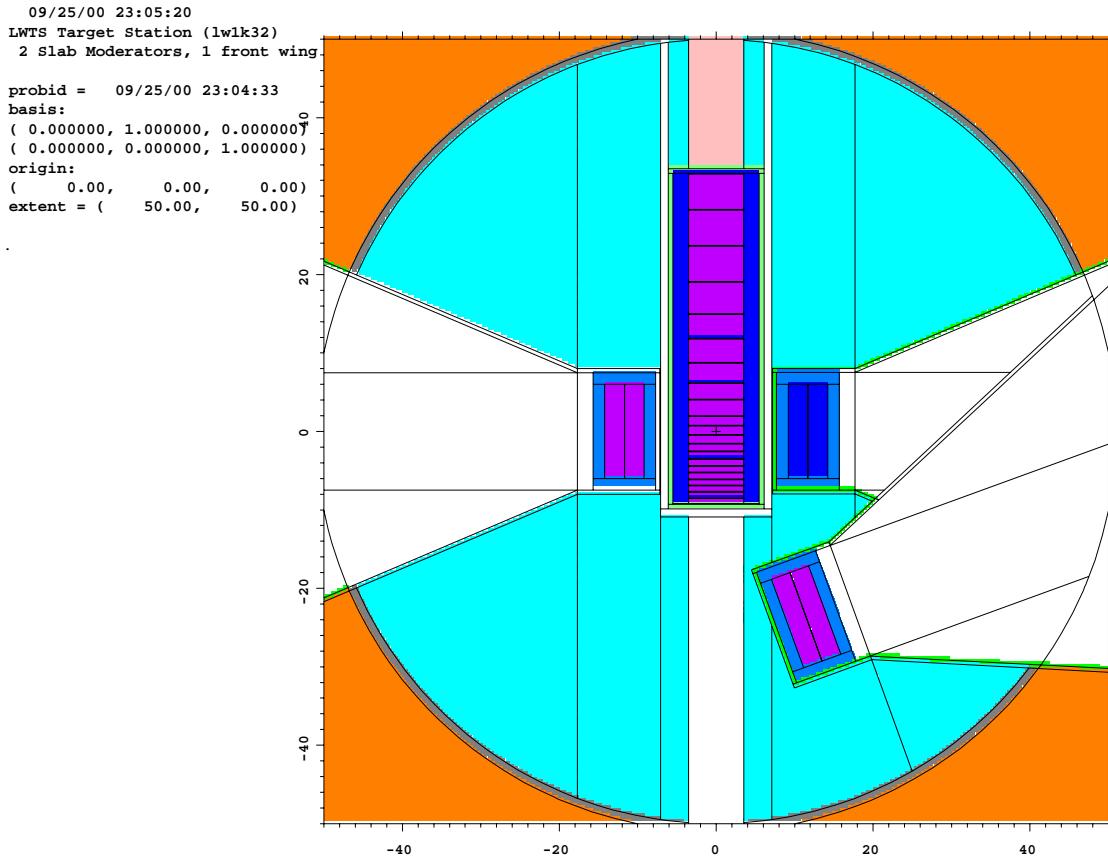


Figure 1: Top view LWTS moderator and target layout. The moderators to the right of the target are decoupled, and both slab moderators are solid methane. Protons enter from the bottom of the figure. Dimensions are in centimeters.

The “port slab” moderator is the slab moderator to the left of the target, when viewed from the direction of the incoming proton beam. This moderator is fully coupled to the reflector, and is composed of solid methane at 22 K (90% by volume) and aluminum (10% by volume). The “starboard slab” moderator is the slab moderator to the right of the target, when viewed from the direction of the incoming proton beam. This moderator is decoupled from the reflector with cadmium, is also composed of solid methane at 22 K (90% by volume) and aluminum (10% by volume), and is poisoned with gadolinium 25 mm beneath the viewed surface. The “front wing” moderator is upstream (for the proton beam) of the target, decoupled with cadmium, poisoned with gadolinium, and composed of liquid methane at 100 K. All moderators are 120 mm (horizontal) by 200 mm (vertical) by 50 mm (depth). Table 2 summarizes this moderator configuration. Note that in our current judgment, all slab moderators must be viewed indirectly, i.e., through a curved guide or compact beam bender.

Moderator Location	Moderator Material	Temperature (K)	Decoupling Material	Poison Material	Poison Depth (mm)
Port Slab	Solid Methane	22	—	—	—
Starboard Slab	Solid Methane	22	Cd	Gd	25
Front Wing	Liquid Methane	100	Cd	Gd	25

Table 2: LWTS moderator summary. Solid methane is diluted with aluminum at 10% by volume.

1.2 High-Power Target Station

The HPTS configuration used for these comparisons is documented in SNS/TSR-203, excerpted below. HPTS Configuration POI5 includes four moderators, two of which are viewed from both sides. All moderators have nominal viewed faces of 100 mm (horizontal) by 120 mm (vertical). The inner reflector (out to a radius of ≈ 320 mm) is beryllium and is cooled with heavy water. This inner reflector is surrounded by heavy water-cooled lead. Table 3 summarizes relevant characteristics of the target station configuration used for this set of calculations. Table 4

Proton Energy	1 GeV
Pulse Rate	60 Hz
Average Power	2 MW
Energy per pulse	34 kJ
Proton Beam Shape	rectangular
Proton Beam Size	200x70 mm ²
Proton Pulse	$\delta(t)$
Target	Hg
Inner Reflector	Be
I.R. Coolant	D ₂ O
Outer Reflector	Pb
O.R. Coolant	D ₂ O

Table 3: HPTS parameters used in calculations. All normalizations are performed per 34 kJ-pulse.

summarizes this moderator configuration.

Beam-line	Moderator Location	Moderator Material	Temperature (K)	Decoupling Material	Poison Material	Poison Depth (mm)
2	TU	H ₂	20	Cd	Gd	27
5	TD	H ₂	20	—	—	—
8	BU	Composite	—	Cd	Gd	30
11	TU	H ₂	20	Cd	Gd	27
14	BD	H ₂ O	300	Cd	Gd	27
17	BU	Composite	—	Cd	Gd	30

Table 4: HPTS moderator summary. Hydrogen is 20–27 K supercritical, modeled as 20 K liquid.

2 Moderators Compared

Table 5 shows the LWTS and HPTS moderators selected for comparison here. This is by no means an exhaustive

ID Code	Target Station	Moderator Material	T (K)	Decoupling Material	Poison Material	Poison Depth (mm)
source_lw1k32_cosmsl	LWTS	Solid Methane	22	–	–	–
source_lw1k32_desmsl	LWTS	Solid Methane	22	Cd	Gd	25
source_poi203_td_05_03	HPTS	Hydrogen	20	–	–	–
source_poi203_tu_11_03	HPTS	Hydrogen	20	Cd	Gd	25

Table 5: Moderators compared in detail, and ID codes for corresponding data files.

comparison. The moderators in Table 5 are representative, and include decoupled and coupled moderators from both target stations, in the case of each target station the moderator most relevant (by some highly subjective metric) to “long wavelength” neutron work. Although the front wing moderator, which is a part of the base concept for LWTS, is not discussed here, it may be assumed to have an overall coupling intensity of 0.35 that of the slab moderator. The front wing moderator can be directly viewed.

3 Quantities Calculated

The spectral intensity $i(E)$ of a moderator is a measure of the number of neutrons leaving the moderator at a particular energy E , and is related to the differential flux $\phi(E)$ at a point some large distance L from the moderator by

$$i(E) = L^2 \phi(E)|_L , \quad (1)$$

where the flight path is normal to the viewed moderator face. This intensity is thus independent of flight path length. If the flight path is not normal to the moderator surface, the intensity observed is scaled by the cosine of the angle between the flight path and the normal to the moderator surface. The intensity is usually separated into a shape and an overall scale factor, with the overall scale factor equal to the intensity evaluated at 1 eV, referred to as the “moderator coupling.” Note that slab moderators are assumed to require indirect views of the moderator, and thus 1 eV neutrons would likely not be available from those moderators; we nonetheless use the 1 eV coupling as a metric for characterizing the moderator performance.

The emission time distribution of the moderator, also called the pulse shape, is simply the intensity distribution as a function of time (after the initial proton pulse strikes the target) at which neutrons cross the moderator surface,

$$i(E) = \int_0^\infty i(E, t) dt. \quad (2)$$

The emission time distribution of the neutrons leaving the moderator is dependent upon the viewing angle only in the scaling of the overall intensity. The energy binning and time binning for the Monte Carlo calculations provide 10 energy bins and 20 time bins per decade, such that $\Delta E/E \approx 23\%$ and $\Delta t/t \approx 11\%$. The predictions reported are differential values averaged over such bins.

4 Discussion

The LWTS proposal lists several potential gain factors we seek to exploit in the neutronic design of LWTS. Many of these gains are quoted from “the conventional wisdom,” and are somewhat subjective and of uncertain accuracy, as well as being specific to certain cases and situations. These factors are listed in Table 6. The specific characteristics are discussed in greater detail below.

Category	Characteristic	Predicted Gain	
		Coupled	Decoupled
Target-Moderator-Reflector Geometry	Slab Moderators ^b	2.0	2.0
	Flux Trap Moderators ^b	1.5	1.5
	Tall Moderators	2.0	2.0
	Tighter Reflector Coverage	1.2	1.2
Moderator Material/Geometry	Grooved	1.5 ^a	1.5 ^a
	CH ₄ (22 K)	3.5 ^a	3.5 ^a
Target Material	W ^c	1.3 ^a	1.2
	Depleted U-Mo ^c	1.7	1.7
Reflector Material	77 K Be	1.5 ^a	1.2 ^a

(a) (additional) gain is available only at long wavelengths.

(b) mutually exclusive options.

(c) mutually exclusive options.

Table 6: Gain factors sought for LWTS. Some options are mutually exclusive, and not all options have been chosen for the base LWTS design.

4.1 Target-Moderator-Reflector Geometry

“Target-Moderator-Reflector Geometry” covers characteristics of the system such as slab and flux trap moderators, tall moderators, and general questions of completeness of reflector coverage. As such, individual effects are very difficult to separate. If we collect these effects together, we can currently claim an overall gain factor of 2.2, based upon the overall gain of a factor of 2.5 in moderator coupling and separating out the advantage due to target material (discussed below). Recall that the front wing moderator position is lower by a factor of 0.35 as compared to the slab moderator, but can be directly viewed (and thus used for neutrons of all wavelengths).

4.2 Moderator Material

The use of solid methane as a moderator material is canonically assumed to provide an increase in long wavelength neutron intensity of a factor of 3.5. At 1 meV we observe an increase of a factor of 8.6 in spectral intensity for the decoupled moderator. This factor of 8.6 includes the factor of 2.5 from the overall gains described above, and thus moderator material choice can be credited with a factor of 3.4, roughly as expected. For the coupled moderator, however, the 1 meV intensity comparison gives a factor of 4.3 between LWTS and HPTS, of which a factor of 3.4 is due strictly to target-moderator-reflector geometry effects, leaving a small apparent benefit of 25% in overall intensity to be gained by using solid methane on the coupled moderator. It should be noted that moderator sizes and premoderation have not been independently optimized for the moderator materials considered.

4.3 Target Material

Independent optimization studies not reported here indicate that the use of tungsten as a target material, rather than mercury as in HPTS, will result in a 15% gain in 1 eV coupling for the slab moderators, and a 25% total gain in 1 meV intensity for coupled moderators, reflecting the fact that mercury serves as a rather effective decoupling material in itself.

4.4 Reflector Material

The purpose of decoupling a reflector from a moderator is to prevent neutrons thermalized in the reflector from entering the moderator and leaking out with characteristically long time constants determined by the reflector. In a room-temperature reflector, this requires cadmium for decoupling material, based upon the cut-off energy of the transmission cross section and the spectral temperature of the thermalized neutron field within the reflector. If this spectral temperature can be lowered, for example by reducing the physical temperature of the reflector material, the cut-off energy of the decoupler can be simultaneously reduced, increasing the number of neutrons fed into the moderator by the reflector without spoiling the characteristically sharp slowing-down pulse shape. Furthermore, if a reflector is coupled, cooling it will provide a significantly larger, lower-temperature neutron field to feed the coupled moderator, again resulting in a higher neutron intensity at long wavelengths. While this option has not yet been exploited in our base design, we have calculated a variant design (not reported here) where the beryllium is cooled to 77 K, and which results in a 20% increase in long wavelength intensity on decoupled moderators and a 50% increase in long wavelength intensity on coupled moderators.

5 Calculational Techniques

The simulations reported are the results of calculations using the MCNPX code (version 2.1.5) and the Lahet Code System, both from LANL. The spectral intensities shown result from calculations using point detector tallies located 5 m from the viewed surface of the moderator. The emission time distributions (pulse shapes) come from current tallies on the viewed surface of the moderator material, and are averaged over 2π steradians. Weight windows used to accelerate the pulse shape calculations were generated by separate iterative runs using MCNP 4B in parallel mode on a large cluster of machines with a neutron-only source term. MCNPX runs using these weight windows produced the reported results for HPTS, while coupled Lahet-MCNP 4B calculations produced the reported results for LWTS. Both sets of results have further been scaled (from the point detector calculations) to correspond to the intensity coming off of the moderator face in the normal direction, rather than the average over 2π steradians. Each moderator nominally requires a unique set of weight windows, and thus a unique set of runs. In some runs, however, the results for moderators other than the one for which the weight windows were optimized are adequately sampled.

6 Extrapolation

The results of the various simulations are reported, both here and in the source files, over a broad range of energies. In the event that results for energies outside this range are desired, certain extrapolations are reasonable. Spectra can be extrapolated to higher energies by using a simple power law, as they are very nearly, but not exactly, $1/E$ up to energies of approximately 100 keV. Emission time distributions for higher energies (in the slowing-down region) can in general be assumed to be invariant as a function of vt (velocity multiplied by time), equivalent to t/λ . However, the proton pulse at SNS is not actually a delta function in time, but rather has a width of a few hundred nanoseconds. Neutron pulse shapes for energies above 3 eV or so will be influenced by this proton pulse

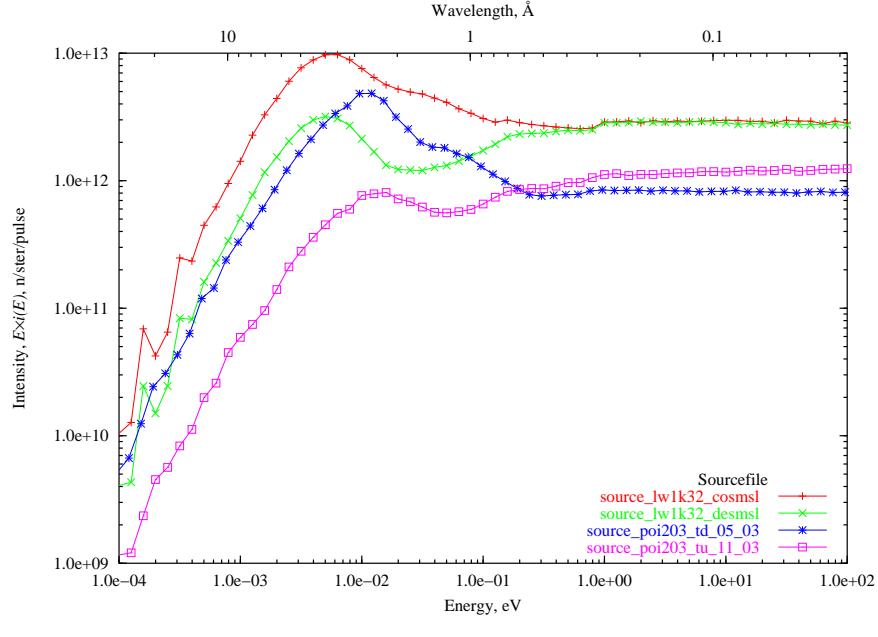
shape, while neutron pulse shapes for energies above 40 eV or so will be completely dominated by the proton pulse shape, and thus will be invariant as a function of time. At low energies, the spectral intensity from water or methane moderators can be assumed to follow a Maxwellian distribution in the low-energy limit. The low-energy intensity from composite or hydrogen moderators can be extrapolated with a power law relationship from the data shown, and will likely not correspond to a Maxwellian distribution.

7 Data Availability

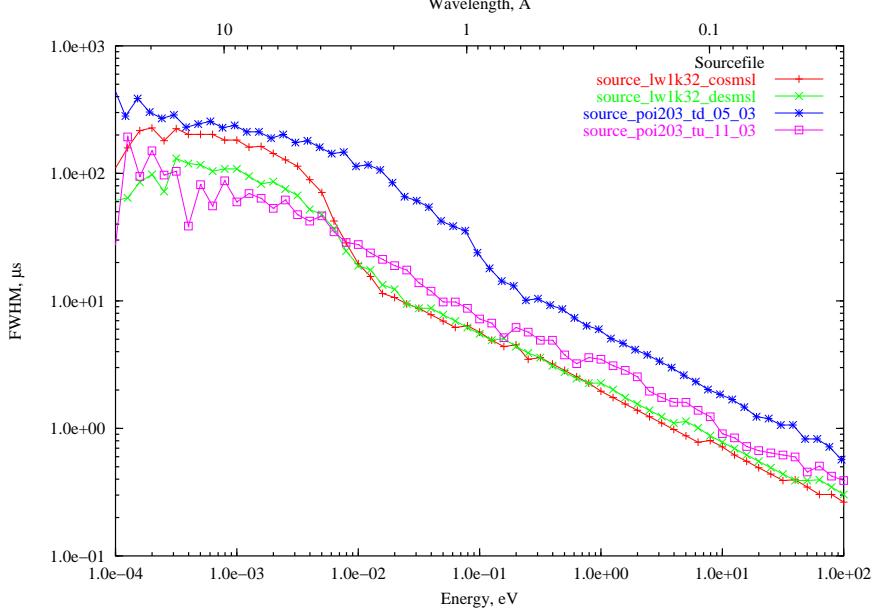
These results are available electronically as “source files;” ASCII files containing the spectra and emission time distributions, with comments showing the file format. Each moderator is represented by a single source file, the names of which are based on the indicated ID codes. These source files can be downloaded from <http://www.sns.anl.gov> under “R&D Projects.”

8 Detailed Pulse Shapes

The detailed pulse shapes as produced by the simulations appear below. These data are completely un-processed, and appear exactly as they result from the calculations. The results are for the different moderators as described in Table 5. Recall that slab moderators must be viewed indirectly, implying a cut-off wavelength below which neutrons are unavailable due to the characteristics of the viewing optics.



(a) Intensity



(b) Pulse Width

Figure 2: Intensity (per unit lethargy) and pulse widths (FWHM) as functions of energy for compared moderators. Recall that slab moderators must be indirectly viewed. The LWTS coupled moderator is denoted source_lw1k32_cosmsl, the LWTS decoupled moderator source_lw1k32_desmst, the HPTS coupled moderator source_poi203_td_05_03, and the HPTS decoupled moderator source_poi203_tu_11_03.

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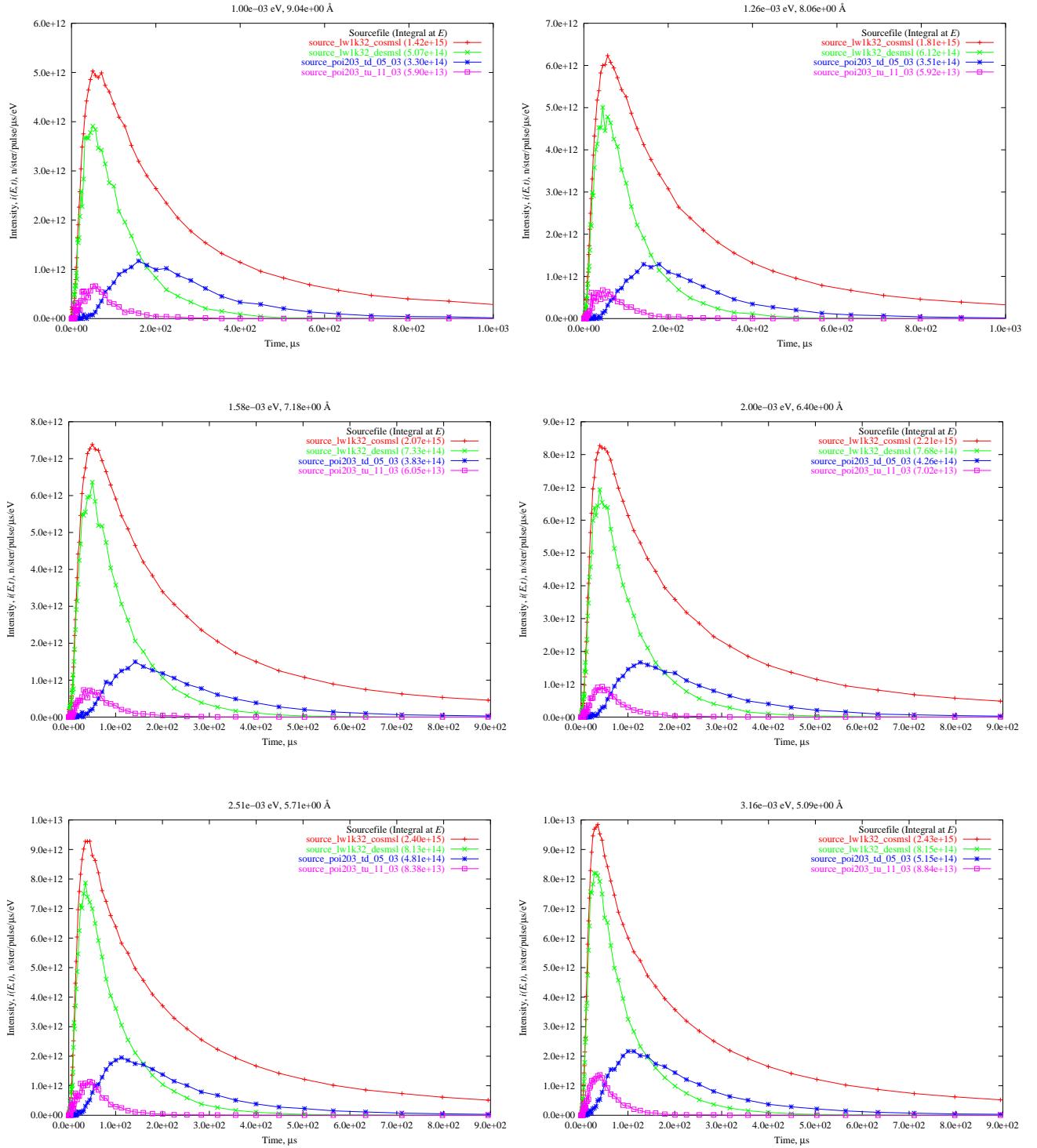


Figure 3: Emission time distributions. The LWTS coupled moderator is denoted `source_lw1k32_cosmnl`, the LWTS decoupled moderator `source_lw1k32_desmnl`, the HPTS coupled moderator `source_poi203_td_05_03`, and the HPT-S decoupled moderator `source_poi203_tu_11_03`. $\Delta E/E \approx 23\%$. Recall that slab moderators must be viewed indirectly.

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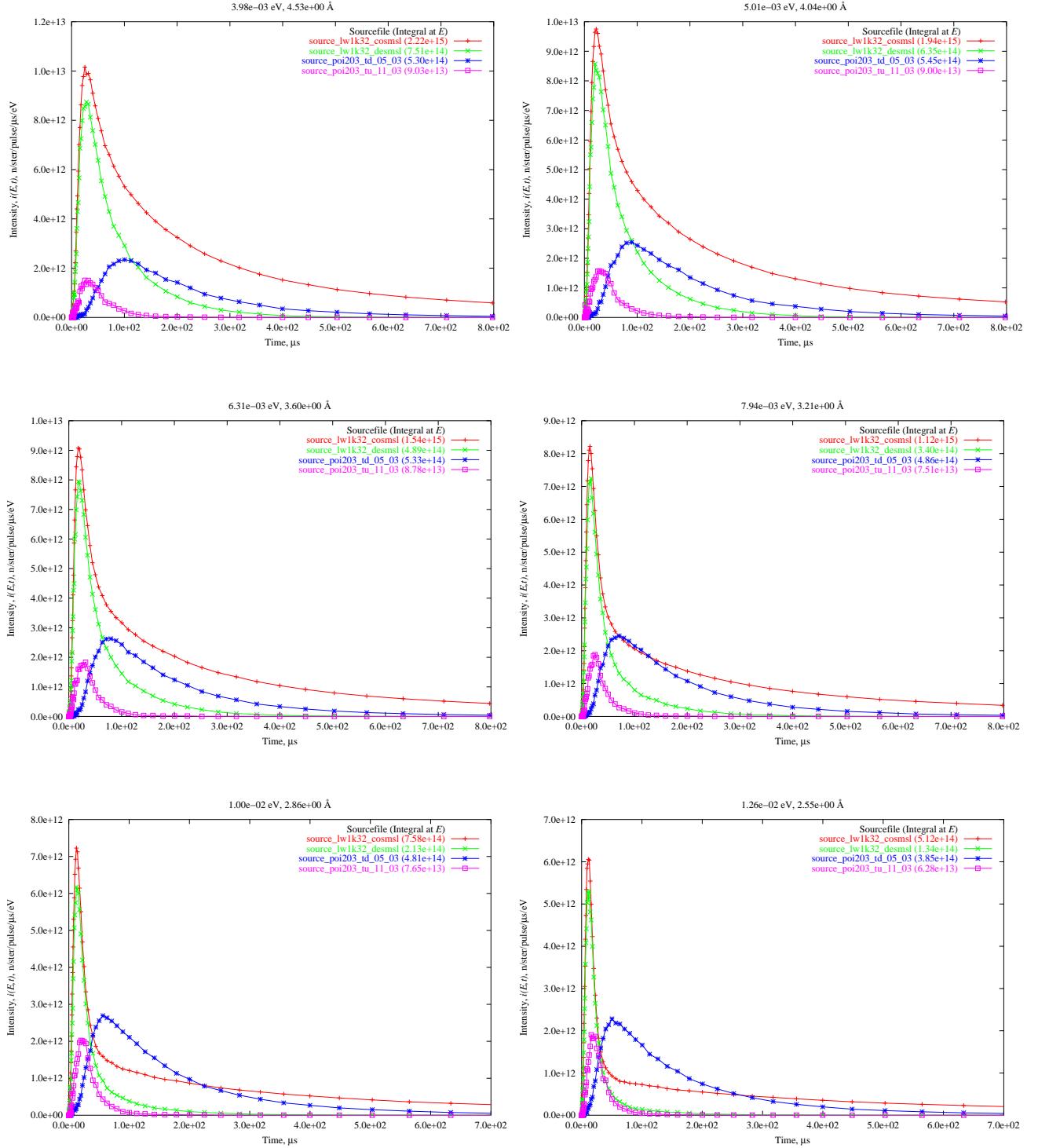


Figure 4: Emission time distributions. The LWTS coupled moderator is denoted `source_lw1k32_cosmsl`, the LWTS decoupled moderator `source_lw1k32_desmsl`, the HPTS coupled moderator `source_poi203_td_05_03`, and the HPT-S decoupled moderator `source_poi203_tu_11_03`. $\Delta E/E \approx 23\%$. Recall that slab moderators must be viewed indirectly.

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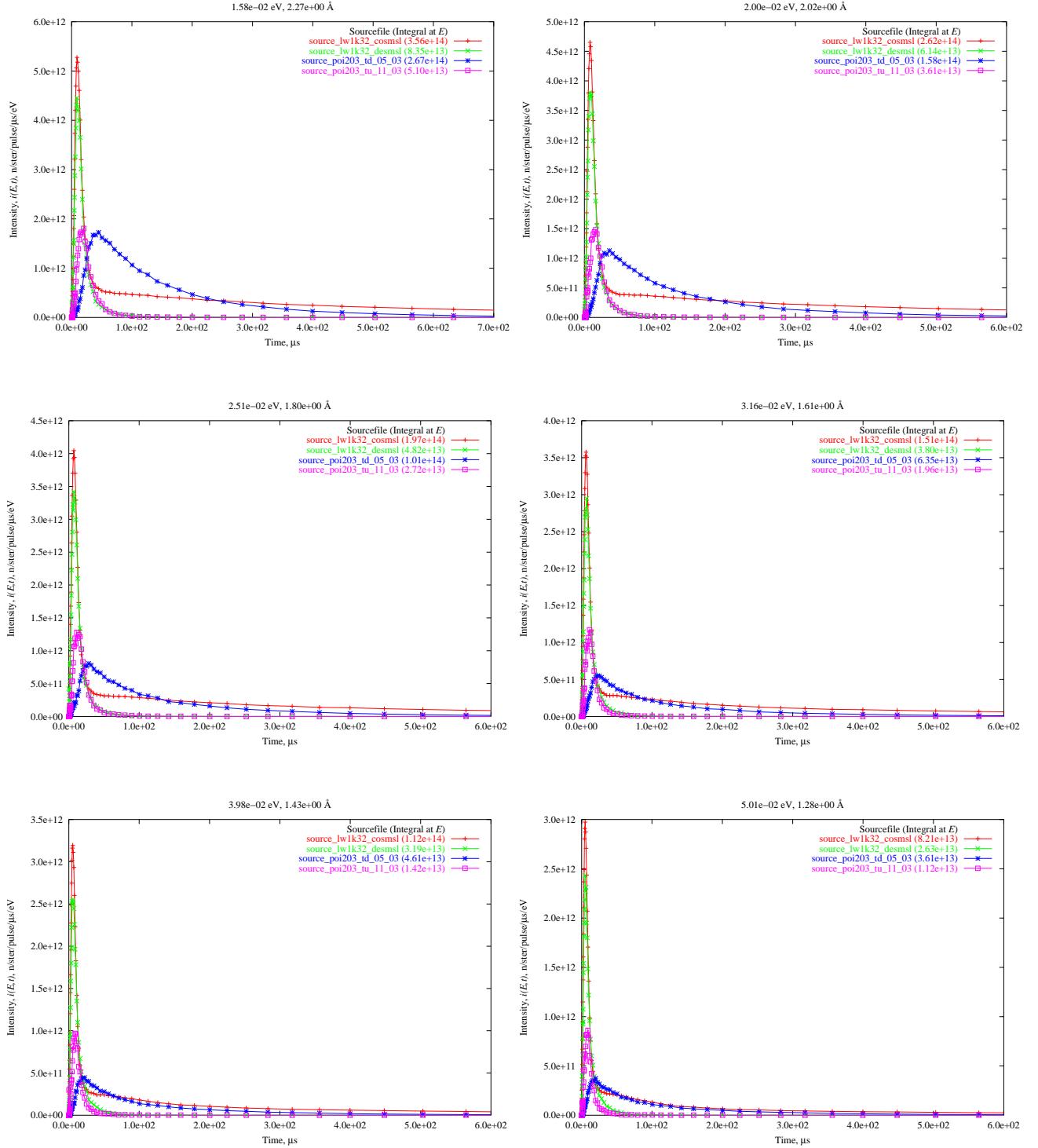


Figure 5: Emission time distributions. The LWTS coupled moderator is denoted `source_lw1k32_cosmsl`, the LWTS decoupled moderator `source_lw1k32_desmsl`, the HPTS coupled moderator `source_poi203_td_05_03`, and the HPT-S decoupled moderator `source_poi203_tu_11_03`. $\Delta E/E \approx 23\%$. Recall that slab moderators must be viewed indirectly.

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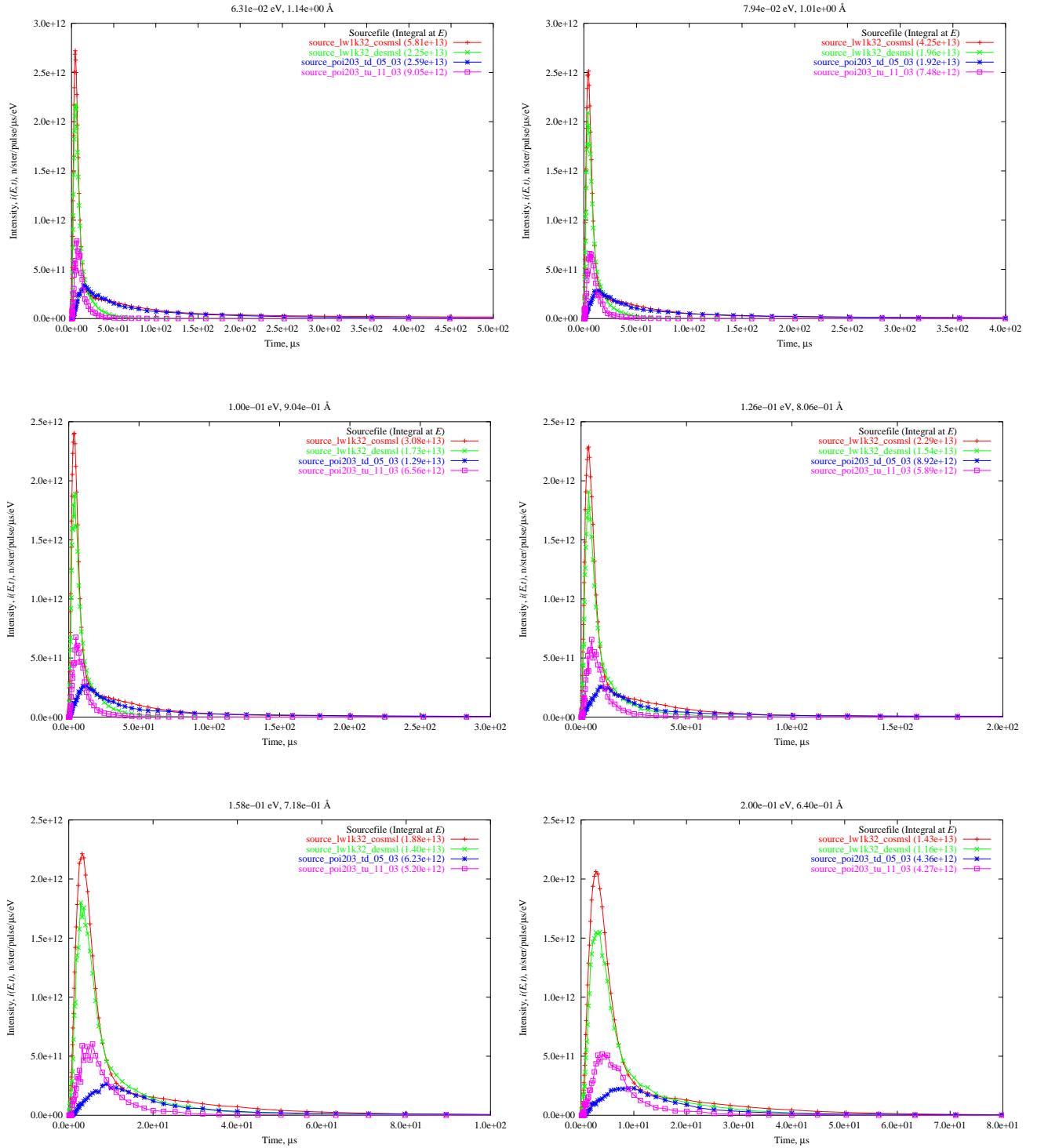


Figure 6: Emission time distributions. The LWTS coupled moderator is denoted `source_lw1k32_cosmsl`, the LWTS decoupled moderator `source_lw1k32_desmsl`, the HPTS coupled moderator `source_poi203_td_05_03`, and the HPT-S decoupled moderator `source_poi203_tu_11_03`. $\Delta E/E \approx 23\%$. Recall that slab moderators must be viewed indirectly.

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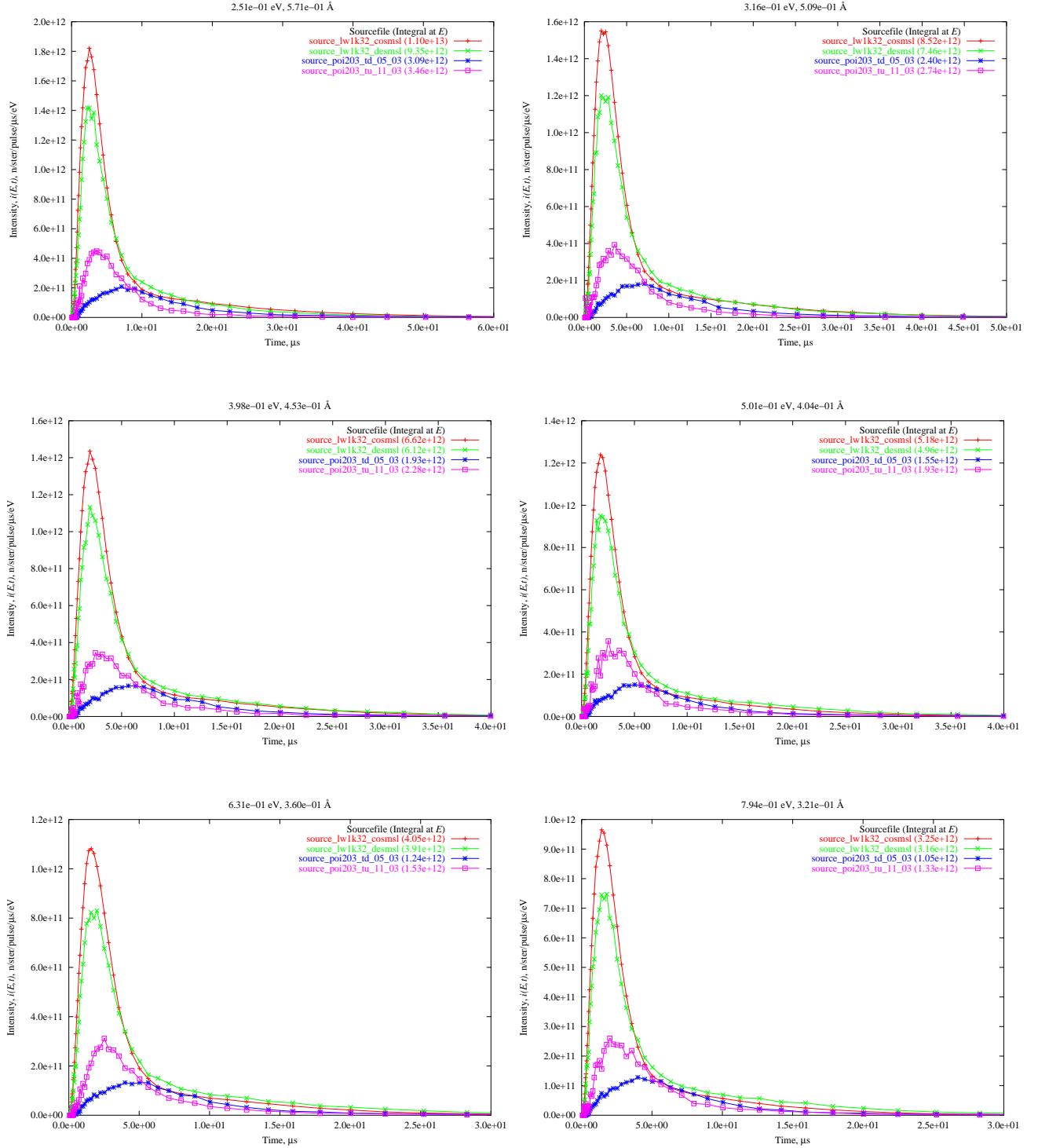


Figure 7: Emission time distributions. The LWTS coupled moderator is denoted `source_lw1k32_cosmsl`, the LWTS decoupled moderator `source_lw1k32_desmsl`, the HPTS coupled moderator `source_poi203_td_05_03`, and the HPT-S decoupled moderator `source_poi203_tu_11_03`. $\Delta E/E \approx 23\%$. Recall that slab moderators must be viewed indirectly.

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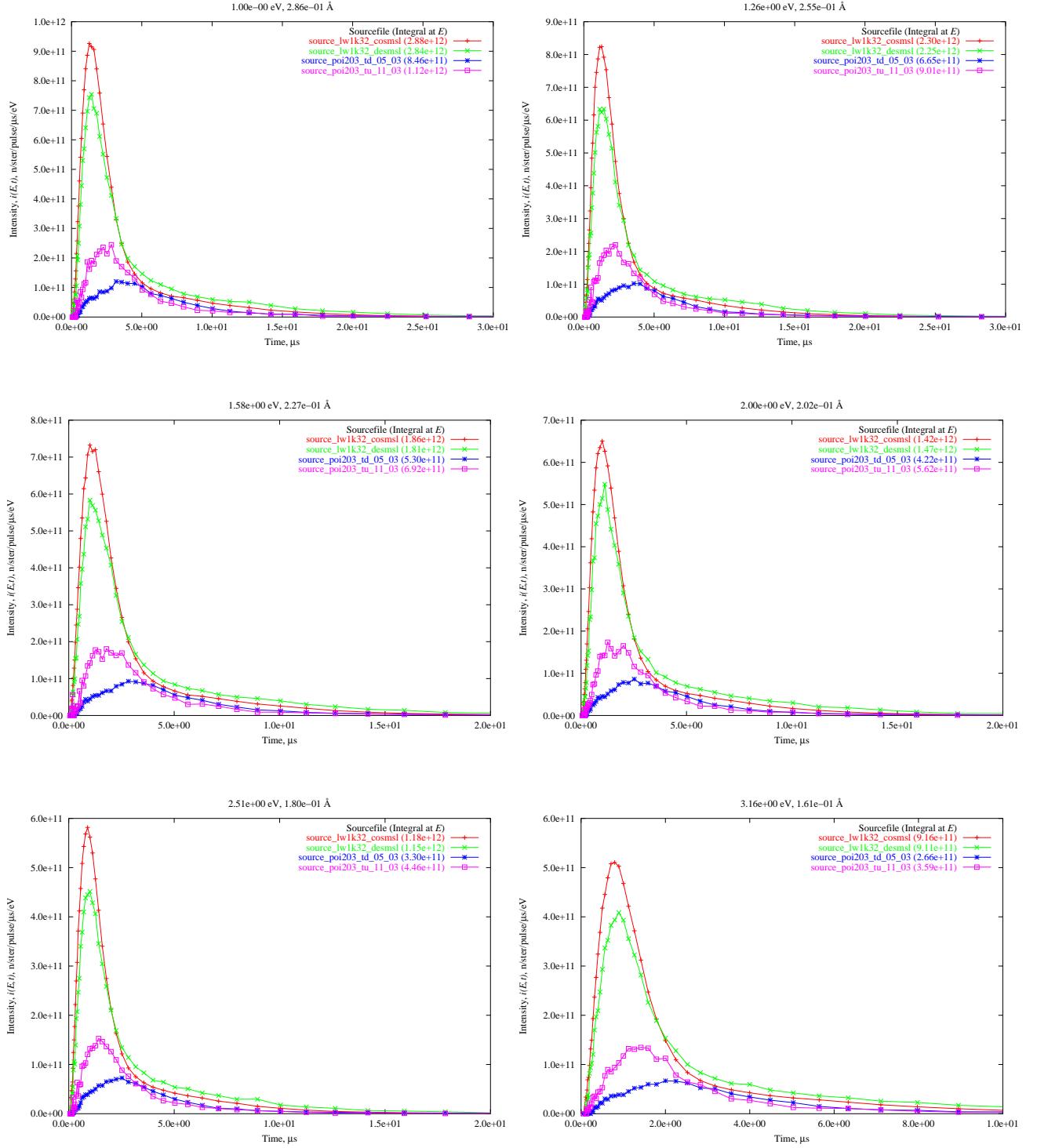


Figure 8: Emission time distributions. The LWTS coupled moderator is denoted source_lw1k32_cosmsl, the LWTS decoupled moderator source_lw1k32_desmsl, the HPTS coupled moderator source_poi203_td_05_03, and the HPT-S decoupled moderator source_poi203_tu_11_03. $\Delta E/E \approx 23\%$. Recall that slab moderators must be viewed indirectly.

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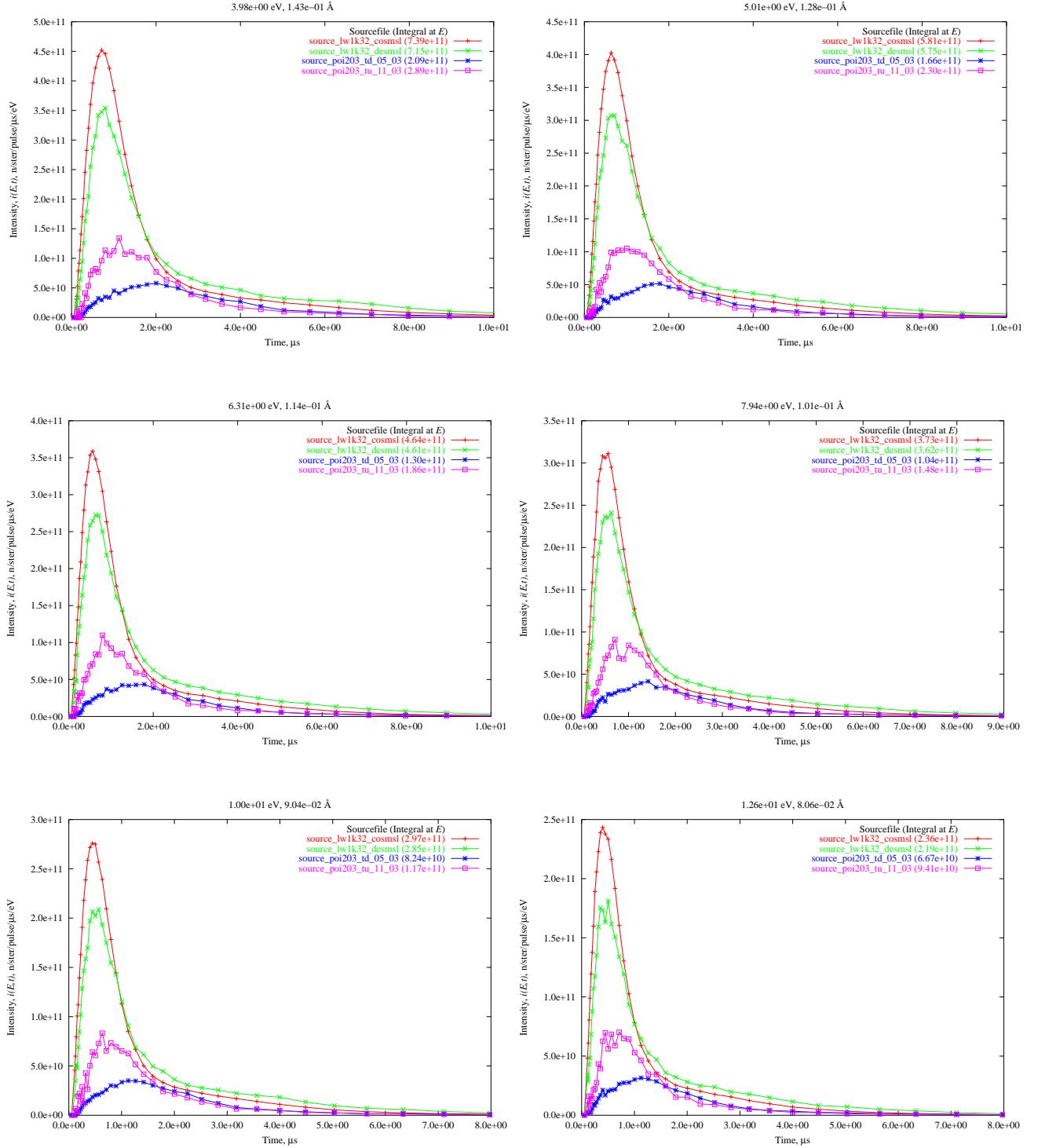


Figure 9: Emission time distributions. The LWTS coupled moderator is denoted source_lw1k32_cosmsl, the LWTS decoupled moderator source_lw1k32_desmsl, the HPTS coupled moderator source_poi203_td_05_03, and the HPT-S decoupled moderator source_poi203_tu_11_03. $\Delta E/E \approx 23\%$. Recall that slab moderators must be viewed indirectly.

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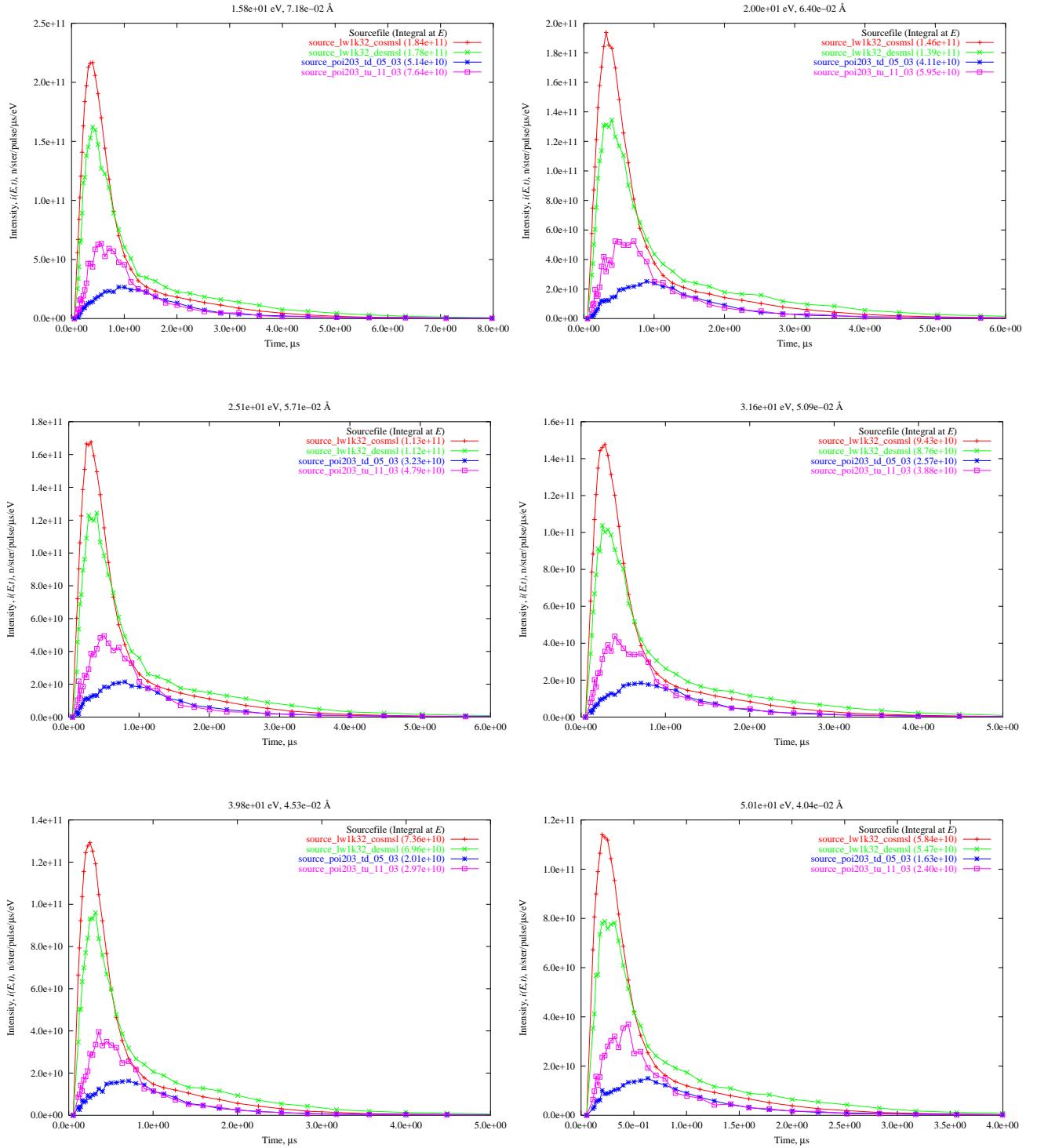


Figure 10: Emission time distributions. The LWTS coupled moderator is denoted source_lw1k32_cosmnl, the LWTS decoupled moderator source_lw1k32_desmnl, the HPTS coupled moderator source_poi203_td_05_03, and the HPT-S decoupled moderator source_poi203_tu_11_03. $\Delta E/E \approx 23\%$. Recall that slab moderators must be viewed indirectly.